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CARBON DIOXIDE EMISSIONS FROM THE GLOBAL CEMENT INDUSTRY*

Ernst Worrell,[1] Lynn Price,[1] Nathan Martin,[1] Chris Hendriks,[2] and Leticia Ozawa Meida[3]

[1]Energy Analysis Department, Lawrence Berkeley National Laboratory, Berkeley, California 94720, [2]Ecofys, 3503 RK, Utrecht, The Netherlands, and [3]Instituto de Ingenieria, Universidad Nacional Autonoma de Mexico, Coyoacan, 04510, Mexico, D.F.; e-mail: Eworrell@lbl.gov, LKPrice@lbl.gov, NCMartin@lbl.gov, C.Hendriks@ecofys.nl, L.Ozawa@uea.ac.uk

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■ **Abstract** The cement industry contributes about 5% to global anthropogenic CO_2 emissions, making the cement industry an important sector for CO_2-emission mitigation strategies. CO_2 is emitted from the calcination process of limestone, from combustion of fuels in the kiln, as well as from power generation. In this paper, we review the total CO_2 emissions from cement making, including process and energy-related emissions. Currently, most available data only includes the process emissions. We also discuss CO_2 emission mitigation options for the cement industry. Estimated total carbon emissions from cement production in 1994 were 307 million metric tons of carbon (MtC), 160 MtC from process carbon emissions, and 147 MtC from energy use. Overall, the top 10 cement-producing countries in 1994 accounted for 63% of global carbon emissions from cement production. The average intensity of carbon dioxide emissions from total global cement production is 222 kg of C/t of cement. Emission mitigation options include energy efficiency improvement, new processes, a shift to low carbon fuels, application of waste fuels, increased use of additives in cement making, and, eventually, alternative cements and CO_2 removal from flue gases in clinker kilns.

CONTENTS

1. INTRODUCTION

The threat of climate change is considered to be one of the major environmental challenges for our society. Carbon dioxide (CO_2) is one of the major greenhouse gases. Anthropogenic sources of CO_2 are the combustion of fossil fuels, deforestation, unsustainable combustion of biomass, and the emission of mineral sources of CO_2. The production of cement contributes to the emission of CO_2 through the combustion of fossil fuels, as well as through the decarbonization of limestone. In this review we focus on the cement industry. Currently available data assesses only emissions from decarbonization of limestone, and there is no inclusive review of the emissions due to energy use in the cement industry. This is the first review of the total CO_2 emissions of the global cement industry.

Cement is one of the most important building materials worldwide. It is used mainly for the production of concrete. Concrete is a mixture of inert mineral aggregates, e.g., sand, gravel, crushed stones, and cement. Cement consumption and production is closely related to construction activity and, therefore, to the general economic activity. Because of the importance of cement as a construction material, and because of the geographic abundance of the main raw materials, cement is produced in virtually all countries. The widespread production is also due to the relatively low price and high density of cement that, in turn, limits ground transportation because of high transport costs.

Cement production is a highly energy-intensive production process. Energy consumption by the cement industry is estimated at about 2% of the global primary energy consumption, or almost 5% of the total global industrial energy consumption (1). Because of the dominant use of carbon-intensive fuels, such as coal in clinker making, the cement industry is a major source of CO_2 emissions. Besides energy consumption, the clinker-making process also emits CO_2 from the calcining process. Because of both emission sources, and because of the emissions from electricity production, the cement industry is a major source of carbon emissions and deserves attention in the assessment of carbon emission-reduction options.

This warrants in-depth research, as climate change mitigation may have profound effects on the cement industry (2–4).

In this paper we review the role of the cement industry in global CO_2 emissions. First we describe the cement production process, the main process variants, and the main emission sources. This is followed by an assessment of historical development and regional development of cement production, followed by an overview of the emissions from cement production. Finally, we provide a brief review of the opportunities for emission reduction, both from the use of fossil fuels and from the calcination process in cement making.

2. PROCESS DESCRIPTION OF CEMENT MAKING

2.1. Cement Properties

Cement is an inorganic, nonmetallic substance with hydraulic binding properties. Mixed with water it forms a paste, which hardens owing to formation of hydrates. After hardening, the cement retains its strength. There are numerous types of cement because of the use of different sources for calcium and different additives to regulate properties. Table 1 gives an overview of important cement types. The exact composition of cement determines its properties (e.g., sulphate resistance, alkali content, heat of hydration), whereas the fineness is an important parameter in the development of strength and rate of setting.

In 1995, global cement production was estimated to be 1453 million metric tons (Mt) (5). Because of the importance of cement as a construction material, and

TABLE 1 Summary of the main cement types, composition, and raw materials needed

Cement type	Composition	Remarks
Portland[a]	95% clinker 5% gypsum	Gypsum improves workability of cement
Portland slag	60% clinker	
Portland pozzolana	40% slag, pozzolana, fly ash	
Portland fly ash		
Iron Portland (Germany)		
Blast furnace	20%–65% clinker 35%–80% blast furnace slag	Only granulated slag can be used, not air cooled
Pozzolanic	60% clinker 40% pozzolana	Important in countries with volcanic materials
Masonry	Mixture of clinker and ground limestone	Binder for brick work

[a]Named Portland because the artificial stone made from the first Portland cement (1824) resembled natural stone from the peninsula Portland.

because of the geographic abundance of the main raw materials, cement is produced in virtually all countries. The widespread production is also due to the relatively low price and high density of cement, which in turn limits ground transportation because of high transport costs. In 1996, global cement trade was 106 Mt of cement, 7% of global cement production.

2.2. Process Description

Cement production is a highly energy-intensive process. Cement making consists of three major process steps (Figure 1): raw material preparation, clinker making in the kiln, and cement making. Raw material preparation and cement making are the main electricity-consuming processes, while the clinker kiln uses almost all the fuel in a typical cement plant. Clinker production is the most energy-intensive production step, responsible for about 70%–80% of the total energy consumed (1). Raw material preparation and finish grinding are electricity-intensive production steps. Energy consumption by the cement industry is estimated at 2% of the global primary energy consumption (1), or 5% of the total global industrial energy consumption. In the process described below, we focus on energy use because of its importance as one of the potential sources of CO_2 emissions.

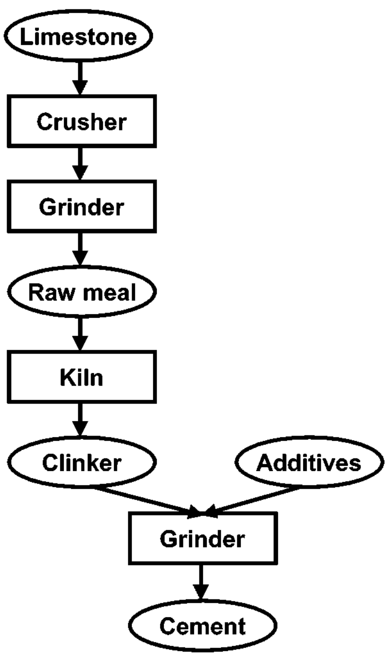

Figure 1 Simplified process schematic of cement making.

2.2.1. RAW MATERIAL PREPARATION The most common raw materials used for cement production are limestone, chalk, and clay, although more than 30 raw materials can be used (6). An exact and constant composition of the raw materials is important for the quality and uniformity of cement. The collected raw materials are selected, crushed, and ground so that the resulting mixture has the desired fineness and chemical composition for delivery to the pyro-processing systems (6, 7). A jaw or gyratory crusher, a roller, or a hammer mill is used to crush the limestone. The crushed material is screened, and stones are removed. Following crushing, the raw materials are further processed. The grinding process differs with the type of pyro-processing used (see below), either using ball or rolling mills. The feed to the kiln is called raw meal. Approximately 1.65–1.75 t of raw meal are needed to produce 1 t of clinker (8).

2.2.2. CLINKER PRODUCTION (PYRO-PROCESSING) Clinker is produced by pyro-processing. The raw meal is burned at high temperatures, first calcining the materials, followed by clinkerization to produce clinker. Various kiln types have been used historically or are used around the world. Besides the rotary kiln, the vertical shaft kiln is used mainly in developing countries. We discuss the general trends in kiln types and development, followed by a discussion of energy use in cement making.

Vertical shaft kilns for clinker production have been in use since the invention of Portland cement in 1824. The intermittent operation of these kilns led to an extremely high energy consumption. Continuous production of clinker started with the use of shaft kilns around 1880, followed by the introduction of the dry rotary kiln. The wet process, fed by slurry, was introduced to achieve better homogenization of the kiln feed, easier operation, less dust, and more uniform cement quality. In 1928, the Lepol, or semi-dry, process was introduced, reducing moisture content of the material entering the kiln and reducing fuel consumption. Improved raw meal homogenization systems and dust collection equipment improved the product quality of the dry process. The long dry kiln, originally introduced in the United States, was relatively inefficient because of high energy losses. The introduction of a dry kiln with material (suspension) preheating reduced the energy costs compared with the commercially used processes in the 1950s. The latest technology development was the introduction of the precalciner in the 1970s, which reduced energy needs further, while boosting productivity when rebuilding existing kilns.

2.2.3. ROTARY KILNS In industrialized countries, the ground raw materials are predominantly processed in rotary kilns. A *rotary kiln* is a tube with a diameter up to about 6 m. The tube is installed at a horizontal angle of 3°–4° and rotates at one to four times per minute. The ground raw material moves down the tube toward the flame. Different types of rotary kilns are in use in the cement industry. If raw materials contain more than 20% water, wet processing (9–11) can be preferable (originally, the wet process was the preferred process, as it was easier to grind and control the composition and size distribution of the particles in a slurry; the need for the wet process was reduced by the development of improved homogenization processes). In the wet process, the slurry typically contains 38% water (range of 24%–48%). The raw materials are then processed in a ball mill to form slurry (with extra water). Variations exist—e.g., semi wet (moisture content of 17%–22%) (9) and semi dry (moisture content of 11%–14%), or Lepol (9, 12–15)—to reduce the fuel consumption in the kiln. The moisture content in the (dried) feed of the dry kiln is typically around 0.5% (0%–0.7%). The dry kiln can be equipped with (multistage) preheaters and a precalciner. Introduction of a preheater reduces the energy requirement of the burning process. A preheater that is especially applicable to the dry process is the suspension preheater (9, 11). Another preheater is the grate preheater, mainly used in semi wet, semi dry, Lepol, and older dry kilns. Pellets or briquettes are placed on a grate that travels through a closed tunnel. Additionally, a precalciner can be integrated between the kiln and the suspension preheater. This is a chamber with a burner, in which 80%–95% of the $CaCO_3$ can be dissociated before entering the kiln. In processing without precalcination, the decomposition (calcination) of $CaCO_3$ to CaO and CO_2 takes place in the kiln. Application of a precalcinator (*a*) reduces energy consumption (16–20), (*b*) reduces the length of the kiln (9), making the kiln less expensive, and (*c*) reduces NOx emissions (16, 17).

Cooling of the clinker can be performed in a grate cooler, a tube (rotary) cooler, or a planetary cooler. In a grate cooler, the clinker is transported on a moving or reciprocating grate, passed by a flow of air. In a tube or planetary cooler, the clinker is cooled in a counter-current air stream. The cooling air serves as combustion air. The largest part of the energy contained in the clinker is returned to the kiln in this way.

The capital costs of cement plants vary for different countries and local conditions. The capital costs of a new green field clinker plant in Canada are estimated at $175–250 (Canadian) per 1-t capacity (12). The operating costs vary widely because of the differences in labor costs, age, and plant type. An overview of US cement plants estimates the average operating costs at $36.4 (US) per t of cement in 1990, including costs for power, fuel, and raw materials (13).

If excess alkali, chlorides, or sulphur are present in the kiln feed and/or fuel, these might vaporize in the kiln and condense in the preheater. This can lead to operating problems and altered cement-setting behavior. There is a higher demand for low alkali cements in the United States and Canada than in Europe (12). In the case of the preheater/precalciner kilns, alkali-rich material must be extracted by means of a bypass, which diverts part of the exhaust gas flow and removes the particulates from it for disposal, increasing heat losses (8).

2.2.4. SHAFT KILN Shaft kilns are used in countries with a lack of infrastructure to transport raw materials or cement, or for the production of specialty cements (21). Today, most vertical shaft kilns can be found in China and India, where the lack of infrastructure, lack of capital, and power shortages favored the use of small-scale local cement plants. In China, this is also the consequence of the industrial development pattern, where local township and village enterprises were engines of rural industrialization, which led to a substantial share of shaft kilns in the total cement production. Regional industrialization policies in India also favored the use of shaft kilns other than the large rotary kilns in major cement-producing areas. In India, shaft kilns represent a growing part of total cement production and established almost 10% of the 1996 production capacity (22). In China, the share is even higher, with an estimated 87% of the output in 1995 (23). Typical capacities of shaft kilns vary between 30 t (fully hand operated) and 180 t (mechanized) of clinker per day (24). Shaft kilns may produce a poor-quality clinker, as it is more difficult to manage all process parameters.

The principle of all shaft kilns is similar, although design characteristics may vary. The pelletized material travels from top to bottom, through the same zones as in a rotary kiln. The kiln height is determined by the time needed for the raw material to travel through the zones, and by operational procedures, pellet composition, and air blown (24). Shaft kilns can reach a reasonable efficiency through efficient heat exchange between the feed and exhaust gases (11, 24). The largest energy losses in shaft kilns are due to incomplete combustion, which results in emissions of CO and volatile organic compounds (VOCs) to the environment.

2.2.5. CEMENT MAKING (FINISH GRINDING) Grinding of cement clinker together with additives to control the properties of the cement (e.g., fly ash, blast furnace slag, pozzolana, gypsum, and anhydrite) can be done in ball mills, roller mills, or roller presses. Combinations of these milling techniques are often applied (see Table 2). Coarse material is separated in a classifier to be returned for additional grinding. Power consumption for grinding depends strongly on the fineness required for the final product and the additives used (12, 25–28). The fineness of the cement influences the cement properties and setting time.

2.3. Energy Use in Cement Making

The theoretical energy consumption for producing cement can be calculated based on the enthalpy of formation of 1 kg of Portland cement clinker, which is about 1.76 MJ (10). This calculation refers to reactants and products at 25°C and 0.101 MPa. In addition to the theoretical minimum heat requirements, energy is required to evaporate water and to compensate for the heat losses. Heat is lost from the plant by radiation or convection and, with clinker, emitted kiln dust and exit gases leaving the process. Hence, in practice, energy consumption is higher. The kiln is the major energy user in the cement-making process. Energy use in the kiln basically depends on the moisture content of the raw meal. Figure 2 provides an overview of the heat requirements of different kiln types (7). Most electricity is consumed in the grinding of the raw materials and finished cement. Power consumption for a rotary kiln is comparatively small, and generally around 17 and

TABLE 2 Energy consumption in cement making processes and process types[a]

Process step	Fuel use (GJ/t of product)	Electricity use (kWh/t of product)	Primary energy (GJ/t of cement)
Crushing			
Jaw crusher		0.3–1.4	0.02
Gyratory crusher		0.3–0.7	0.02
Roller crusher		0.4–0.5	0.02
Hammer crusher		1.5–1.6	0.03
Impact crusher		0.4–1.0	0.02
Raw meal grinding			
Ball mill		22	0.39
Vertical mill		16	0.28
Hybrid systems		18–20	0.32–0.35
Roller Press—integral		12	0.21
Roller Press—pregrinding		18	0.32
Clinker kiln			
Wet	5.9–7.0	25	6.2–7.3
Lepol	3.6	30	3.9
Long dry	4.2	25	4.5
Short dry—suspension preheating	3.3–3.4	22	3.6–3.7
Short dry—preheater & precalciner	2.9–3.2	26	3.2–3.5
Shaft	3.7–6.6	N/A	3.7–6.6
Finish grinding[c]			
Ball mill		55	0.60
Ball mill/separator		47	0.51
Roller press/ball mill/separator		41	0.45
Roller press/separator/ball mill		39	0.43
Roller press/separator		28	0.31

[a]Specific energy use is given per unit of throughput in each process. Primary energy is calculated per tonne of cement, assuming portland cement (containing 95% clinker), including auxiliary power consumption. NA, Not applicable.

[b]Primary energy is calculated assuming a net power generation efficiency of 33% (LHV).

[c]Assuming grinding of Portland cement (95% clinker, 5% gypsum) at a fineness of 4000 Blaine.

23 kWh/t of clinker (including the cooler and preheater fans) (9). Additional power is consumed for conveyor belts and packing of cement. Total power use for auxiliaries is estimated at roughly 10 kWh/t of clinker (9, 14). Table 2 summarizes the typical energy consumption for the different processing steps and processes used.

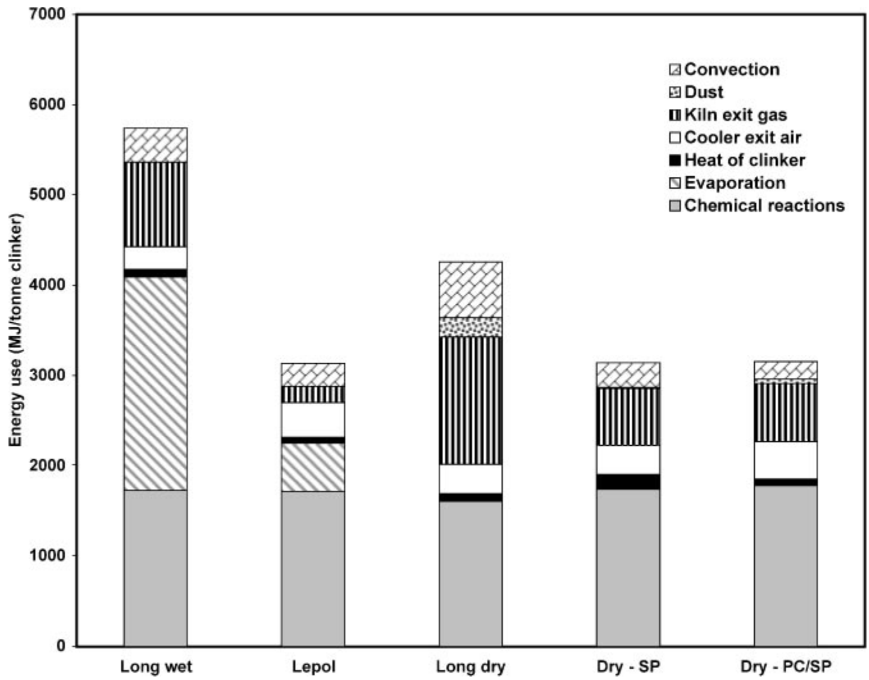

Figure 2 Energy consumption and losses in the major kiln types: Long wet, wet process; Lepol or semi-wet; long dry; Dry-SP, dry process with four-stage suspension preheating; and Dry-PC/SP, dry process with four-stage suspension preheating and precalcining. [Based on data by Van der Vleuten (11).]

3. CEMENT PRODUCTION TRENDS

Global cement production grew from 594 Mt in 1970 to 1453 Mt in 1995 at an average annual rate of 3.6% (5). Cement consumption and production is cyclical, concurrent with business cycles. Historical production trends for 10 world regions are provided in Figure 3. Figure 4 shows production trends in the 10 largest cement-producing countries from 1970 to 1995. The regions with the largest production levels in 1995 were China (including Hong Kong), Europe, Organization for Economic Cooperation and Development (OECD)-Pacific, rest-of-Asia, and the Middle East.

As a region, China (including Hong Kong) clearly dominates current world cement production, manufacturing 477 Mt in 1995, more than twice as much as the next-largest region. Cement production in China increased dramatically between 1970 and 1995, growing from 27 Mt to 475 Mt, at an average annual growth rate of 12.2%. See Table 3. Following rapid growth during the period 1970–1987,

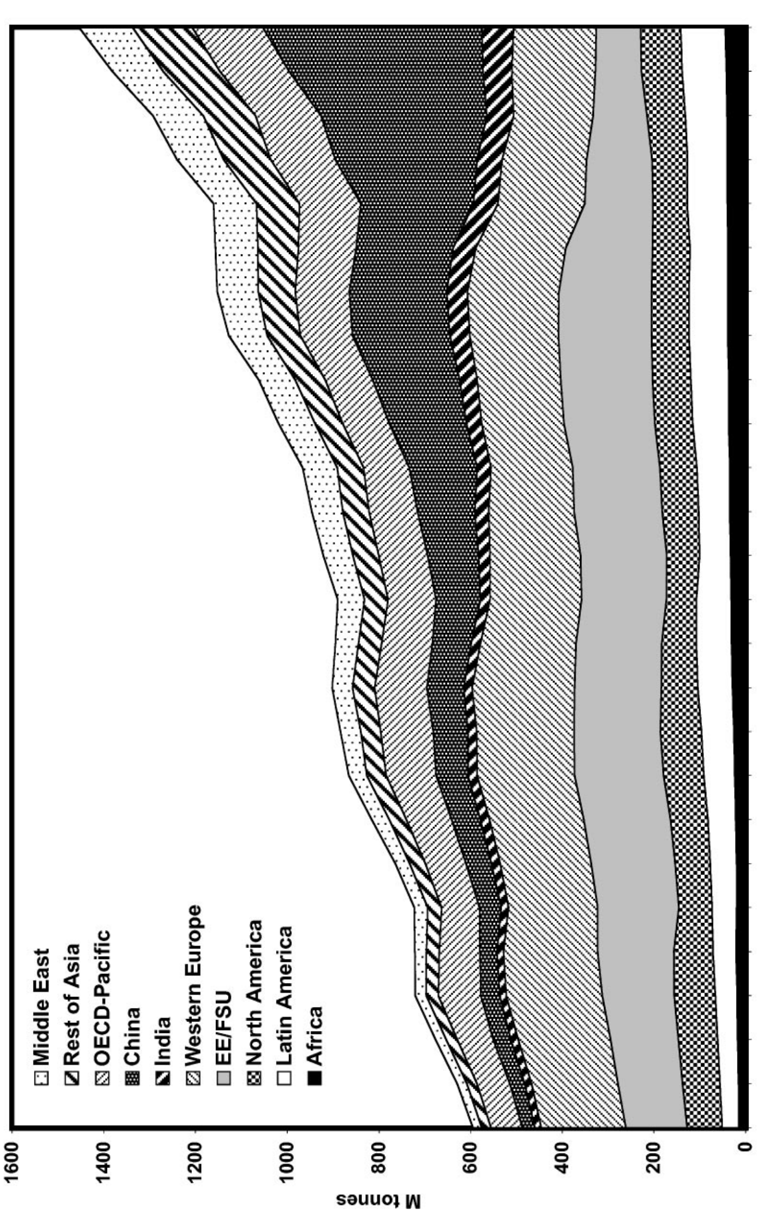

Figure 3 Historical production trends for cement production in 10 regions in the world.

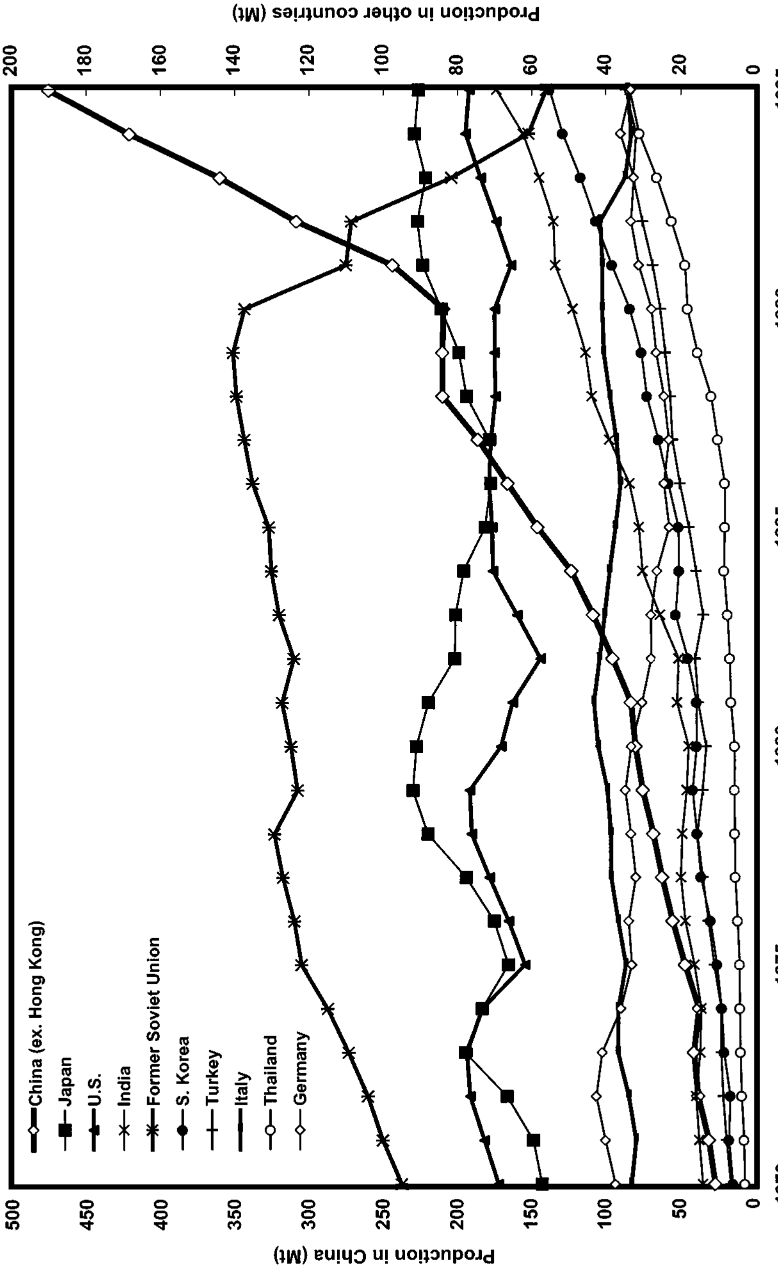

Figure 4 1970-1995 cement production trends in the 10 largest cement-producing countries in 1995 (China only on left-hand axis).

TABLE 3 Cement production trends and average annual growth rates for major world regions and 20 largest cement-producing countries, 1970–1995 (5)

	Cement production						Average annual growth	
	1970	**1975**	**1980**	**1985**	**1990**	**1995**	**1970–1995**	**1990–1995**
Region/country	**Mt**	**Mt**	**Mt**	**Mt**	**Mt**	**Mt**	**%**	**%**
China	26.90	47.48	81.49	147.79	211.15	476.91	12.2%	17.7%
China (excluding Hong Kong)	26.50	46.90	80.00	145.96	209.70	475.00	12.2%	17.8%
Europe	184.61	194.22	223.28	178.04	196.47	180.62	−0.1%	−1.7%
Italy	33.13	34.63	41.93	37.36	40.86	34.21	0.1%	−3.5%
Germany	37.48	32.98	33.14	22.95	27.71	33.30	−0.5%	3.7%
Spain	16.54	24.40	39.63	24.20	28.66	28.49	2.2%	−0.1%
France	29.33	30.66	30.56	23.55	27.05	20.70	−1.4%	−5.2%
OECD-Pacific	68.51	82.55	113.12	99.92	125.79	154.07	3.3%	4.1%
Japan	57.26	66.33	91.15	72.56	84.46	90.59	1.9%	1.4%
South Korea	5.82	10.13	15.57	20.50	33.58	55.13	9.4%	10.4%
Rest of Asia	20.08	30.55	48.77	57.16	88.67	130.09	7.8%	8.0%
Thailand	2.63	3.99	5.30	7.91	18.04	33.65	10.7%	13.3%
Indonesia	0.56	1.09	5.83	9.61	15.78	23.25	16.1%	8.1%
Taiwan	4.54	6.80	14.06	13.56	18.40	22.41	6.6%	4.0%
Middle East	19.31	29.28	44.25	74.85	92.76	116.29	7.4%	4.6%
Turkey	6.37	10.89	13.01	17.67	25.38	34.75	7.0%	6.5%
Egypt	3.69	3.59	3.11	5.28	15.15	17.22	6.4%	2.6%
Iran	2.58	5.00	8.00	12.46	15.06	16.85	7.8%	2.3%
Saudi Arabia	0.67	1.13	2.91	9.85	11.49	15.77	13.5%	6.5%
Latin America	35.62	52.46	75.57	71.25	82.44	97.28	4.1%	3.4%
Brazil	9.00	16.74	27.19	20.64	25.85	28.26	4.7%	1.8%
Mexico	7.18	11.61	16.26	20.68	23.83	24.20	5.0%	0.3%
Eastern Europe/ former Soviet Union	134.13	177.23	189.53	189.62	189.71	96.25	−1.3%	−12.7%
Former Soviet Union	95.23	122.04	124.80	130.77	137.35	56.05	−2.1%	−16.4%
Poland	12.18	18.54	18.44	14.86	12.36	14.65	0.7%	3.5%
North America	76.34	72.69	79.24	80.86	81.04	87.51	0.5%	1.5%
U.S.	69.05	61.82	68.24	70.67	69.95	76.90	0.4%	1.9%
India	13.99	16.21	17.76	31.15	48.90	69.57	6.6%	7.3%
Africa	14.53	19.60	28.36	34.58	38.45	43.94	4.5%	2.7%
World	594.03	722.26	901.36	965.21	1155.72	1452.53	3.6%	4.7%

cement production stabilized from 1988 to 1990 because of a combination of economic austerity measures, inflation, and political instability. However, cement production doubled between 1990 and 1994 because of a construction boom (29). In many respects, China's cement industry is unique in the large number of plants, the broad range of ownership types, and the variety of production technologies. Unlike other heavy industries, cement output is not dominated by a small number of large "key" enterprises. In 1995, large plants with capacities in excess of 100 kt per year produced only 28% of the 476 Mt of cement manufactured. By late 1994, China had over 7500 cement plants spread across the country. Chinese plants tend to be small, with an average output in the neighborhood of somewhat over 50 kilo tons per year, about one tenth that of the average plant in the United States.

Cement production in the Western Europe region was relatively stable between 1970 and 1995, with average annual growth of −0.1%. In 1995, production reached 181 Mt. The largest cement-producing countries in this region are Italy, Germany (defined as West Germany only to 1990; East and West Germany from 1991 to 1995), Spain, and France (30–32).

In 1995, the OECD-Pacific region produced 154 Mt of cement, predominately in Japan and South Korea. Average annual growth in this region was 3.3% between 1970 and 1995. Cement production in Japan grew from 57 Mt in 1970 to 91 Mt in 1995 (31, 33). South Korean cement production grew at the high rate of 9.4% per year between 1970 and 1995. See Table 3. Much of the growth in cement demand since 1993 was the result of a government economic development plan that encouraged both public and private infrastructure investments (34).

The rest-of-Asia region experienced a high average annual growth of 7.7% between 1970 and 1995, jumping from production of 20 Mt of cement in 1970 to 130 Mt in 1995. The largest producing countries in this region are Thailand, Indonesia, and Taiwan (31, 35). Thailand is currently operating the world's largest cement kilns.

Production of cement in the Middle East region also grew rapidly between 1970 and 1995, averaging 7.4% per year. Growth in production slowed slightly beginning in 1990, averaging 4.6% per year through 1995. The largest cement-producing countries in this region are Turkey, Egypt, Iran, and Saudi Arabia (31, 36).

Brazil and Mexico dominate production of cement in the Latin American region; together they are responsible for 54% of the production in this region. Brazil experienced rapid growth in cement production between 1970 and 1980, whereas in the following decade, Brazil experienced an economic crisis and cement production dropped from 27 Mt in 1980 to 19.5 Mt in 1984, climbing slowly back to 28 Mt in 1995 (31, 37). Mexican cement production grew from 7 Mt in 1970 to 24 Mt in 1995, at an average annual rate of 5.0%.

In the Eastern Europe/former Soviet Union region, cement production grew at an average rate of 2.3% per year between 1970 and 1988. After the breakup of the Soviet Union and the major restructuring that began in that region in 1988, production levels dropped by –12.7% per year on average between 1990 and 1995. Cement production in the former Soviet Union grew steadily from 95 Mt in 1970 to 140 Mt in 1989. After the dissolution of the Union of Soviet Socialist Republics in the late 1980s, production in the region dropped dramatically, falling to 56 Mt in 1995. Countries of the former Soviet Union with the highest production levels in 1995 were the Russian Federation (36 Mt), Ukraine (10 Mt), and Uzbekistan (4 Mt) (38).

Cement production in the North American region was relatively stable between 1970 and 1995, growing only 0.5% per year on average. See Table 3. Recent economic growth has led to increased cement demand. Production of cement in the United States fluctuated between 58 Mt and 78 Mt, with large drops following the oil price shocks in 1973 and 1979 (31, 39).

In the Indian region, cement production in India grew from 14 Mt to 70 Mt between 1970 and 1995, at an average annual rate of 6.6%. Growth in production was slower, averaging 3.3% per year, between 1970 and 1982. Currently, the Indian cement industry is the fourth largest cement producer in the world. In 1982, the Indian government began to deregulate the cement industry, allowing companies to establish prices and production volumes (40, 41). As a result, production levels tripled between 1982 and 1995 and average growth reached almost 10% per year.

The African region showed relatively high growth between 1970 and 1995, jumping from 14.5 Mt to 44 Mt at an average annual rate of 4.5%. This growth appears to have slowed recently, increasing an average of 2.7% per year between 1990 and 1995. The largest cement-producing African countries are South Africa, Algeria, and Morocco, although none is among the top 20 cement-producing countries worldwide.

4. GLOBAL CARBON DIOXIDE EMISSIONS FROM CEMENT MAKING

Carbon dioxide emissions in cement manufacturing come directly from combustion of fossil fuels and from calcining the limestone in the raw mix. An indirect and significantly smaller source of CO_2 is from consumption of electricity, assuming that the electricity is generated from fossil fuels. Roughly half of the emitted CO_2 originates from combustion of the fuel and half originates from the conversion of the raw material. Not accounted for are the CO_2 emissions attributable to mobile equipment used for mining of raw material, used for transport of raw material and cement, and used on the plant site. Current emission estimates for the cement industry are based solely on the assumed clinker production (derived from cement production assuming Portland cement) and exclude emissions due to energy use. Emissions from energy use are included in the estimates for emissions from energy use, and not allocated to cement making.

We provide an overall estimate of total CO_2 emissions based on production trends and energy use. Because of the difficulty of data collection (especially for clinker production), we have only estimated the emissions for the year 1994. This estimate is based on current, publicly available data for the cement sector (42–57). CO_2 emissions were calculated in several steps. First, the top 27 cement-producing countries, accounting for 83% of cement production in 1994, were identified according to 10 regional groupings [Africa, Latin America, North America, Eastern Europe and the former Soviet Union, Europe, India, China, OECD Pacific, other-Asia, Middle East]. These key countries formed the basis of our global estimate. The remaining 132 countries were grouped within the rest of each region (e.g., “rest-of-Africa”).

4.1. Carbon Dioxide Emissions from Calcination

Process CO_2 is formed by calcining, which can be expressed by the following equation:

$$\begin{array}{ccc} CaCO_3 \rightarrow & CaO + CO_2 \\ 1\,\text{kg} & 0.56\,\text{kg} + 0.44\,\text{kg}. \end{array}$$

The share of CaO in clinker amounts to 64%–67%. The remainder consists of silicon oxides, iron oxides, and aluminum oxides. Therefore, CO_2 emissions from clinker production amount to about 0.5 kg/kg. The specific process CO_2 emission per tonne of cement depends on the ratio of clinker to cement. This ratio varies normally from 0.5 to 0.95.

We estimated the amount of clinker produced in the key countries in order to calculate process CO_2 emissions associated with clinker production. For the process emissions, a calcination factor of 0.136 Mt of carbon (MtC)/t of clinker (0.5 Mt of CO_2/t of clinker) (1 Mt of CO_2 = 0.27 MtC = 0.27 Tg of C) was applied to each metric ton of clinker produced. Actual clinker production data were collected for Brazil, Mexico, the United States, Canada, Germany, India, China, Japan, and Korea (29, 41–44). For other key countries, clinker production was estimated by referring to data from previous years or by assuming that clinker capacity utilization for 1994 was the same as cement utilization capacity calculated from Cembureau statistics (45, 46). For those non-key countries for which no specific clinker production data were available, we used an estimated average for the clinker/cement (C/C) ratio. We divided the countries into industrialized countries and rest-of-world and into two groupings for C/C ratio—84% for industrialized countries and 87% for rest-of-world—based on a weighted average of actual clinker to cement ratio data collected for key countries.

4.2. Carbon Dioxide Emissions from Fuel Use

Practically all fuel is used during pyro-processing: Fuel is burned in the kiln. The amount of CO_2 emitted during this process is influenced by the type of fuel used (coal, fuel oil, natural gas, petroleum coke, alternative fuels). CO_2 emission factors (EF_{CO2}) of fuels are based on emission factors defined by the Intergovernment Panel on Climate Change (47). The direct EF_{CO2} of waste fuels is considered to be zero, because the input of waste replaces an equivalent amount of fossil fuel–derived energy, and the CO_2 would probably have been released (in the short or long term) to the atmosphere without useful application of the energy content. If the waste is used in competition with alternative uses, the replacement of fossil fuel and the avoidance of CO_2 emissions should be considered in more depth.

To calculate energy-related CO_2 emissions from fossil fuel consumption, we first reviewed 1994 data on the average specific fuel consumption per tonne of clinker (gigajoules per tonne) for key countries, or for the closest year to 1994 for which there was available data. Actual intensity data for industrialized countries were collected for Canada, Germany, France, Italy, Japan, Korea, Spain, Turkey, and the United States (9, 42–44, 46, 48–50). Available fuel intensity data for developing countries and for Eastern Europe and the former Soviet Union included that from Argentina, Brazil, China, Columbia, Egypt, India, Mexico, Poland, and Venezuela (11, 29, 51–54). For other key countries (Morocco, South Africa, Ukraine, Thailand, Taiwan, Indonesia, Saudi Arabia, and Iran), we used Cembureau statistics and calculated the share of wet and dry kiln technology per country. We then applied an intensity factor of 5.9 GJ/t of clinker for wet kilns and 3.5 GJ/t of clinker for dry kilns to calculate weighted fuel intensity for these countries. For countries where fuel intensity data were not available, we sorted them into two groupings—industrialized countries and rest-of-the-world—and applied an average weighted fuel intensity (based on actual key country data collected) of 3.5 GJ/t of clinker for industrialized countries and 4.2 GJ/t of clinker for rest-of-world countries. We then used national statistics and Cembureau data to calculate weighted carbon emissions factor of fossil fuel inputs (47) for cement production by country. A weighted fuel carbon emission factor was calculated for the rest-of-region grouping.

4.3. Carbon Dioxide Emissions from Electricity Use

The final step for estimating CO_2 emissions was to calculate emissions from electricity consumption. Specific electricity consumption data was reviewed for the same key industrialized and developing countries as was collected for fuel consumption data (Canada, Germany, France, Italy, Japan, Korea, Spain, Turkey, United States, Argentina, Brazil, China, Columbia, Egypt, India, Mexico, Poland, and Venezuela). For all other countries and regional groupings, electricity intensity for all kilns was estimated at 0.3 GJ/t of cement for industrialized countries and 0.4 GJ/t of cement for rest-of-the-world. International Energy Agency statistics were used to calculate the average carbon intensity of fuel inputs for public electricity generation for each country and regional grouping (55).

4.4. Total Carbon Dioxide Emissions from Cement Production

Estimated carbon emissions from cement production in 1994 were 307 MtC, 160 MtC from process carbon emissions and 147 MtC from energy use. These emissions account for 5.0% of 1994 world carbon emissions based on a total of 6199 MtC reported by the Carbon Dioxide Information and Analysis Center (56).

Table 4 and Figure 5 provide CO_2 emissions estimates (in million metric tons of carbon) by key cement-producing countries and regions. Of the countries shown, China accounts for by far the largest share of total emissions (33.0%), followed by the United States (6.2%), India (5.1%), Japan (5.1%), and Korea (3.7%). Overall, the top 10 cement-producing countries in 1994 accounted for 63% of global carbon emissions from cement production for that year. Regionally, after China, the largest emitting regions are Europe (11.5%), OECD-Pacific (9.3%), Asian countries excluding China and India (9.3%), and the Middle East (8.4%). World average primary energy intensity was 4.8 GJ/t, with the most energy-intensive regions being Eastern Europe and the former Soviet Union (5.5 GJ/t), North America (5.4 GJ/t), and the Middle East (5.1 GJ/t).

The average world carbon intensity of carbon emissions in cement production is 222 kg of C/t of cement. Although China is the largest emitter, the most carbon-intensive cement region in terms of carbon emissions per tonne of cement produced is India (253 kgC/t), followed by North America (242 kgC/t), and then China (240 kgC/t). Figure 6 shows the carbon intensity of cement production in various regions.

5. REDUCTION OF CARBON DIOXIDE EMISSIONS

Many opportunities exist for CO_2 emission reduction in the cement industry. We provide only a brief review of the wide body of literature.

5.1. Energy Efficiency Improvement

Improvement of energy efficiency reduces the emissions of CO_2 from fuel and electricity uses and may reduce the costs of producing cement. Improvement may be attained by using more energy-efficient equipment and by replacing old installations with new ones or shifting to completely new types of cement production processes. By far the largest proportion of energy consumed in cement manufacture consists of fuel that is used to heat the kiln. Therefore, the greatest gain in reducing energy input may come from improved fuel efficiency. In general, the dry process is more energy efficient than the wet process. The processes are exchangeable to a large extent, but the applicability may be limited by the raw material available (i.e., moisture content). The main opportunities in the kiln are the conversion to more energy-efficient process variants (e.g., from a wet process to a dry process with preheaters and precalciner), optimization of the clinker cooler, improvement of preheating efficiency, improved burners as well as process control and management systems. Electricity use can be reduced through improved grinding systems, high-efficiency classifiers, high-efficiency motor systems, and process control systems (57, 58).

Several studies have demonstrated the existence of cost-effective potentials for energy efficiency improvement in the cement industry. In China, various programs have developed technologies to improve the efficiency of shaft kilns by increased mechanization, insulation, bed distribution, and control systems (24). They found an energy efficiency improvement potential between 10% and 30% for all shaft kilns. A recent study of the Indian cement industry (59) found a technical potential for energy efficiency improvement of almost 33% with commercially available technology. It is estimated that future technologies will bring the energy savings to almost 48%. This would lead to CO_2 emission reductions of 27%. However,

TABLE 4 Global carbon emissions from cement production, 1994[a]

Country	Cement production	C/C ratio	Primary intensity	Primary energy	Process carbon emission	Carbon emission/ energy use	Total carbon emission	Share of world total
	Mt	%	GJ/t	PJ	MtC	MtC	MtC	%
China	423	83%	5.0	2117	47.7	53.7	101.4	33.0%
Europe	181.9		4.1	749	20.0	15.3	35.3	11.5%
Italy	33.2	80%	4.5	150	3.6	3.2	6.8	2.2%
France	21.2	74%	4.1	88	2.1	1.5	3.6	1.2%
Germany	36.1	79%	3.8	137	3.9	2.8	6.7	2.2%
Spain	26.7	81%	3.9	104	2.9	2.5	5.5	1.8%
Rest-of-Europe	64.7	84%	4.2	271	7.4	5.2	12.5	4.1%
OECD-Pacific	151.3		3.5	533	17.6	11.0	28.6	9.3%
Japan	91.6	80%	3.1	280	9.9	5.7	15.6	5.1%
Korea	51.6	96%	4.3	220	6.7	4.6	11.4	3.7%
Rest of OECD-Pacific	8.0	84%	4.2	34	0.9	0.7	1.6	0.5%
Other-Asia	123.8		4.9	613	15.3	13.3	28.6	9.3%
Thailand	31.1	90%	4.8	148	3.8	3.4	7.2	2.4%
Taiwan	23.2	95%	4.9	114	3.0	2.5	5.5	1.8%
Indonesia	21.9	96%	5.3	115	2.9	2.4	5.3	1.7%
Rest-of-other-Asia	47.6	87%	4.9	235	5.6	4.9	10.5	3.4%
Middle East	111.2		5.1	563	13.8	12.0	25.8	8.4%
Saudi Arabia	16.0	87%	4.7	75	1.9	1.4	3.3	1.1%
Egypt	16.1	99%	5.8	93	2.2	1.9	4.1	1.3%
Iran	15.9	97%	5.3	84	2.1	1.6	3.7	1.2%
Turkey	31.9	90%	4.9	156	3.9	4.1	8.0	2.6%
Rest-of-Middle-East	31.4	87%	4.9	155	3.7	3.0	6.7	2.2%

North America	88.4		5.4	480	10.6	10.8	21.4	7.0%
US	77.9	88%	5.5	427	9.3	9.6	18.9	6.2%
Canada	10.5	88%	5.1	53	1.3	1.2	2.5	0.8%
EE/FSU	100.7		5.5	558	11.4	10.3	21.7	7.1%
Poland	14.9	82%	5.6	83	1.7	2.1	3.8	1.2%
Ukraine	11.4	80%	6.0	68	1.3	1.3	2.6	0.8%
Russia	37.2	80%	6.0	223	4.1	3.8	7.8	2.5%
Rest-of-EE/FSU	37.1	87%	4.9	183	4.4	3.2	7.6	2.5%
Latin America	97.4		4.7	462	11.2	8.2	19.4	6.3%
Brazil	25.2	77%	4.1	102	2.6	1.7	4.4	1.4%
Mexico	29.8	88%	4.5	133	3.6	2.5	6.0	2.0%
Colombia	8.3	82%	6.1	51	0.9	1.0	2.0	0.6%
Venezuela	7.5	87%	5.7	43	0.9	0.6	1.5	0.5%
Argentina	6.3	90%	5.3	33	0.8	0.5	1.3	0.4%
Rest-of-Latin-America	20.2	87%	4.9	100	2.4	1.9	4.2	1.4%
India	62.4	89%	5.0	309	7.6	8.2	15.8	5.1%
Africa	41.0		4.9	201	4.9	4.2	9.0	2.9%
Morocco	6.3	85%	4.8	30	0.7	0.8	1.5	0.5%
South Africa	7.9	90%	4.9	39	1.0	1.0	1.9	0.6%
Rest-of-Africa	26.8	87%	4.9	132	3.2	2.4	5.6	1.8%
World total	1380.9	85%	4.8	6585	160	147	307	100%

[a]C/C, clinker/cement; OECD; EE/FSU, Eastern Europe/former Soviet Union.

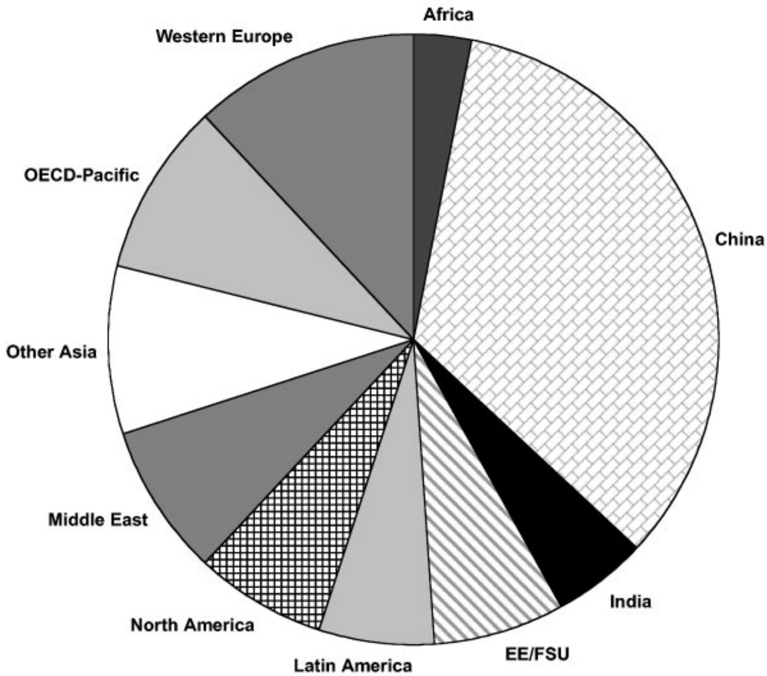

Figure 5 Share of carbon emissions from cement production by world region, 1994.

the economic potential for energy efficiency improvement is estimated at 24% of total primary energy use (using a discount rate of 30%). Martin et al. (58) studied the energy efficiency opportunities in the US cement industry in detail. Focusing on commercially available technology, they identified 29 energy-efficient technologies that could still be adopted to some extent by the US cement industry. Together these have a technical potential for energy efficiency improvement of 40%. However, the economic potential (using a discount rate of 30%) is estimated at only 11% because of the high capital costs and low energy costs in the United States. This limits the CO_2 emission reduction potential to only 5%. If the US cement industry would increase its use of blended cement (see below), the economic potential might increase to 18%, reducing total CO_2 emissions by 16%.

5.2. Replacing High-Carbon Fuels with Low-Carbon Fuels

One option for lowering CO_2 emissions is to reduce the carbon content of the fuel, e.g., shifting from coal to natural gas. An important opportunity to reduce the long-cycle carbon emission is the application of waste-derived alternative fuels. This could at the same time diminish the disposal of waste material and

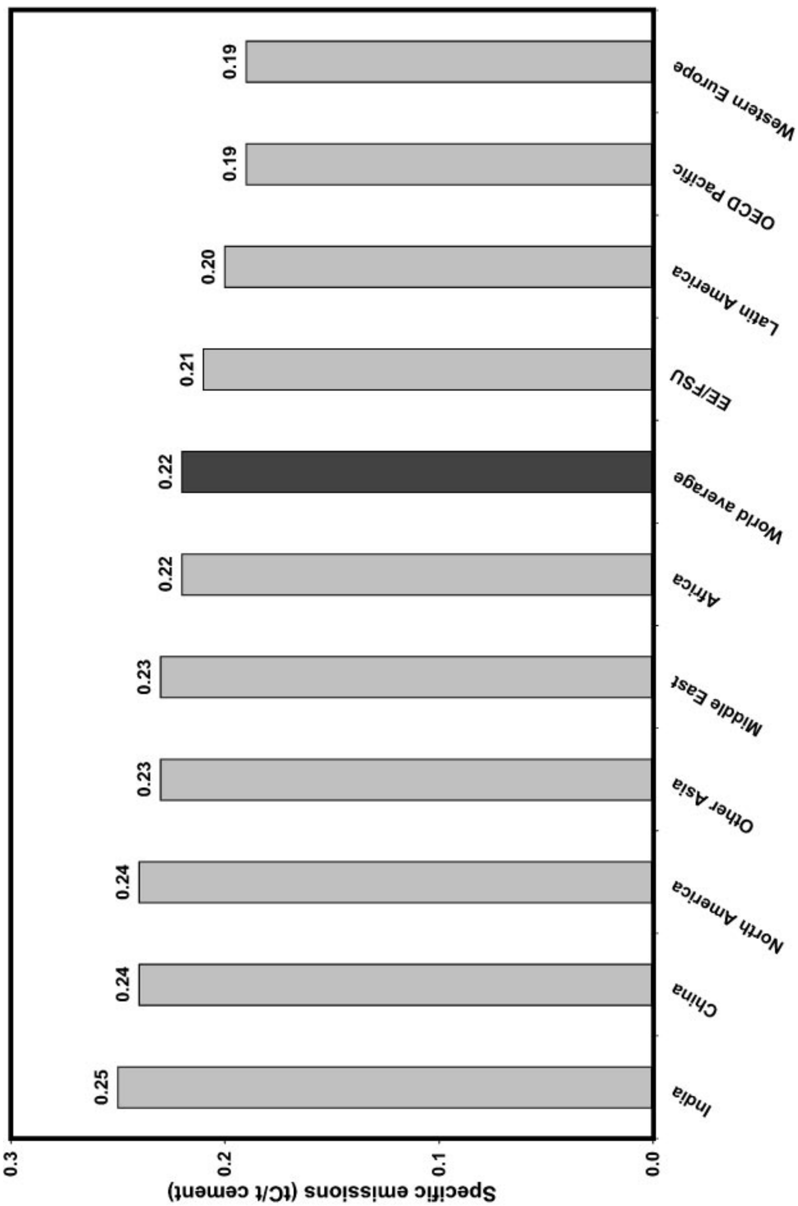

Figure 6 Carbon intensity of cement production in different regions (tonnes of carbon per tonne of cement).

reduce the use of fossil fuels. A number of issues should be considered when using waste-derived fuels: (*a*) energy efficiency of waste combustion in cement kilns; (*b*) constant cement product and fuel quality; (*c*) emissions to atmosphere; (*d*) trace elements and heavy metals; (*e*) alternative fate of waste; and (*f*) production of secondary waste. Disadvantages may be the adverse effects on the cement quality and increased emission of harmful gases. It should be noted that emissions generally depend more on kiln operation conditions than on type of fuel. Alternative fuels may be gaseous (e.g., landfill gas), liquid (e.g., halogen-free spent solvents, distillation residues, waste oils), or solid (e.g., waste wood, dried sewage sludge, plastics, tires). The net emission reduction depends on the nature and characteristics of the wastes, as well as on the waste-treatment process that is displaced (57).

Waste processing in the cement industries is feasible and is a current practice. Waste as alternative fuel is increasingly used in cement plants. In 1990, the European cement industry used between 0.75 Mt and 1 Mt per year of alternative fuels, equivalent to 25–35 PJ. In 1993, 9% of the thermal energy consumption in the European cement industry originated from alternative fuels. Waste may reduce CO_2 emissions by 0.1–0.5 kg/kg of cement produced compared with current production techniques using fossil fuels. The use of waste generates no additional emissions, although care should be taken for highly volatile elements like mercury and thallium (57).

5.3. Blended Cements

The production of clinker is the most energy-intensive step in the cement manufacturing process and causes large process emissions of CO_2. In blended cement, a portion of the clinker is replaced with industrial by-products, such as coal fly ash (a residue from coal burning), blast furnace slag (a residue from ironmaking), or other pozzolanic materials (e.g., volcanic material). These products are blended with the ground clinker to produce a homogenous product: blended cement. Blended cement has different properties than Portland cement, e.g., setting takes longer but ultimate strength is higher (60).

The current application of additives in cement making varies widely by country and region (see Table 4). Although the use of blended cements is common in Europe, it is less common elsewhere, e.g., in North America. The relative importance of additive use can be expressed by the C/C ratio of the cement production in a specific country. Portland cement has a C/C ratio of 0.95, whereas blast furnace slag cement may have a C/C ratio as low as 0.35. Countries such as the United States, Canada, and United Kingdom have high C/C ratios, showing the dominance of Portland cement, whereas countries such as Belgium, France, and the former Soviet Union show lower C/C ratios, expressing the relatively larger use of blended cements (45). Because no international sources collect clinker production data, it is not possible to accurately estimate the current practices in all cement-producing countries. In Table 4 we have used a regional estimate on the basis of information of key countries. The major barriers to further application of blended cements do not seem to be supply or environmental issues but rather existing product standards and specifications as well as building codes (57).

The future potential for application of blended cements depends on the current application level, on the availability of blending materials, and on standards and legislative requirements. The global potential for CO_2 emission reduction through producing blended cement is estimated to be at least 5% of total CO_2 emissions from cement making (56 Mt of CO_2) but may be as high as 20%. The potential savings will vary by country and by region. Worrell et al. (45) estimated the potential for carbon emission reduction on a national basis for 24 countries in the OECD, Eastern Europe, and Latin America. They estimated the minimum availability of blending materials on the basis of pig iron production and coal combustion. The potential emission reduction varied between 0% and 29%. The average emission reduction for all countries (producing 35% of world cement in the reference year 1990) was estimated at 22%. It was negligible for countries with a large share of blended cement production (e.g., The Netherlands) or with a low availability of blending materials, i.e., countries without iron production or coal fired power stations (e.g., Costa Rica, Guatemala). It was high for countries with limited production of blended cements and a well-developed industry or fossil-based power industry (e.g., United Kingdom, United States). The C/C ratio for China was estimated at 85%. Considering the large iron production and coal use in power production in China, a large potential for blended cement may also be expected in the world's largest cement maker.

The costs of blending materials depend strongly on the transportation costs and may vary between $15 and $30 (US) per t for fly ash and approximately $24 (US) per t for blast furnace slag. Shipping costs may increase the price significantly, depending on distance and shipping mode. The prices are still considerably lower than the production costs of cement, estimated at approximately $36 (US) per t (1990) in the United States (57).

Additives such as fly ash contain high concentrations of heavy metals, which under unfavorable conditions may leach into the environment. No negative environmental effects of slag and fly ash addition in cement have been found (57). Only the use of nonferrous slags seems to be limited to slag contents of 15% by mass. However, fly ash and blast furnace slag may be considered hazardous wastes under environmental legislation in some countries, limiting the use of fly ash to specified companies. In the United States, fly ash falls under the Resource Conservation and Recovery Act and gives the states the jurisdiction to define fly ash as a hazardous waste. In practice, the state regulation varies greatly across the United States, which limits the reuse of fly ash.

5.4. Carbon Dioxide Removal

Reduction of CO_2 emissions can be obtained by applying CO_2 removal. In this technique, CO_2 is separated during or after the production process and subsequently stored or disposed of outside the atmosphere. The CO_2 can be recovered from the flue gases, originating from the calcination process as well as from the combustion processes. Typical CO_2 concentrations in the flue gases range from 14% to 33%. Because of the high share of CO_2 in flue gases originating from the calcination process (and not from a combustion process), combustion in a CO_2/O_2 atmosphere may be suitable to recover the CO_2. In the CO_2/O_2 technique, oxygen instead of air is used for the combustion, i.e., the nitrogen is removed in an air-separation plant before the fuel is oxidized. A problem is the high stoichiometric combustion temperatures, which can be solved by recycling produced CO_2. The CO_2 acts as a temperature moderator. No practical experiences with this technique have yet been gained in the cement industry (57). In principle this process could be applied to the cement-production process. A mixture of oxygen and CO_2 is fed to the burner in the kiln. In comparison with the production plant without CO_2 removal, a number of aspects need further exploration (i.e., control of leakage of air into the kiln; cooling of the cement after the kiln; energy balance of the system; consequence of the higher CO_2 partial pressure on the calcination process; and control to reduce emission of CO_2 during start/stops of the cement plant). This technology is currently not cost-effective and needs further research to assess the technical and commercial applicability (57).

6. CONCLUSIONS

The cement industry is a large contributor to global CO_2 emissions. CO_2 is emitted from the calcination process of limestone, from combustion of fuels in the kiln, and from power generation for purchased or self-generated electricity. Estimated carbon emissions from cement production in 1994 were 307 MtC, 160 MtC from calcination, and 147 MtC from energy use. These emissions account for 5% of 1994 global anthropogenic CO_2 emissions. Data collection for this effort is labor intensive, and we recommend that the emissions be reported in future years on a consistent basis.

China accounts for by far the largest share of total emissions (33%), followed by the United States (6%), India (5%), Japan (5%), and Korea (4%). Overall, the top 10 cement-producing countries in 1994 accounted for 63% of global carbon emissions from cement production for that year. Regionally, after China, the largest emitting regions are Europe (12%), OECD-Pacific (9%), Asian countries excluding China and India (9%), and the Middle East (8%).

World average primary energy intensity was 4.8 GJ/t, with the most energy-intensive regions being Eastern Europe and the former Soviet Union (5.5 GJ/t), North America (5.4 GJ/t), and the Middle East (5.1 GJ/t). The average world carbon intensity of carbon emissions in cement production is 222 kg of C/t of cement. Although China is the largest emitter, the most carbon-intensive cement region in terms of carbon emissions per tonne of cement produced is India (253 kg of C/t), followed by North America (242 kg of C/t), and China (240 kg of C/t).

Emissions of CO_2 can be reduced by improvement of the energy efficiency of the process, shifting to a more energy-efficient process (e.g., from wet to dry process), replacing high-carbon fossil fuels with low-carbon fossil fuels or with alternative fuels, and applying lower C/C ratio through production of blended cements. Production of blended cements seems a promising option to reduce both fuel- and process-related CO_2 emissions on the short term. In the long term, application of alternative cements (mineral polymers from kaolin) or the removal of CO_2 from the flue gases may contribute to further CO_2 emission reductions. Both require substantial research and development efforts to assess the applicability and emission-reduction potential. In the short term, energy efficiency improvement, construction of efficient new kilns, increased production of blended cements, and increased use of waste fuels are the most cost-effective measures to reduce CO_2 emissions. The economics of a shift to low-carbon fuels depends on the regional costs of the various fuels.

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